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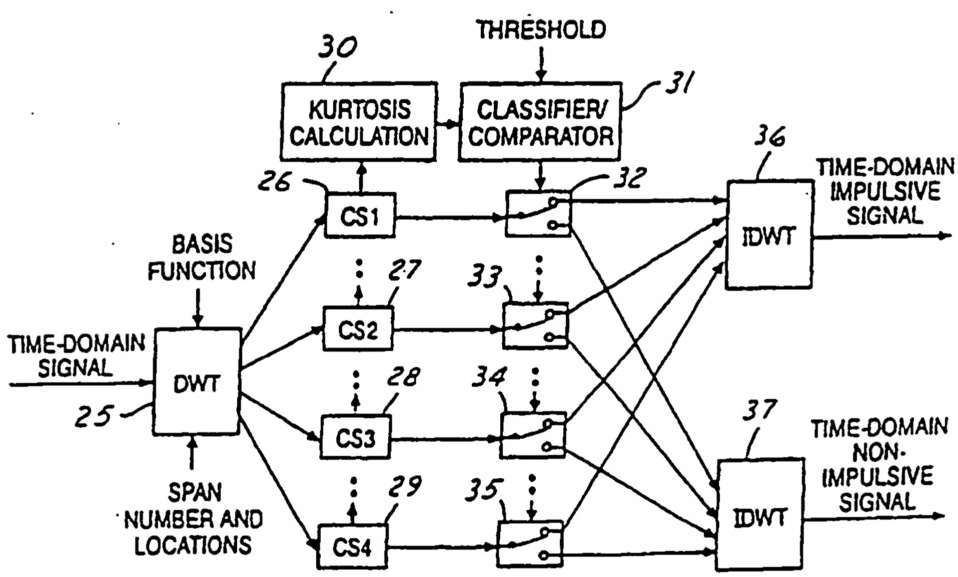

(57) Abstract

Impulsive components and non-impulsive components within any time-domain signal such as audio, video, vibration, etc., are separated using wavelet analysis and sorting of wavelet coefficient sets according to statistical parameters of each respective coefficient set. Each entire coefficient set is either included or excluded from each respective separated component based on the statistical parameter. Thus, automatic, adaptive, flexible, and reliable separation of impulsive and non-impulsive components is achieved.

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SI	Slovenia
SK	Slovakia
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SZ	Swaziland
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METHOD AND APPARATUS FOR SEPARATION OF IMPULSIVE AND NON-IMPULSIVE COMPONENTS IN A SIGNAL

The present invention relates in general to separating impulsive and non-impulsive signal components within a time-domain signal, and more specifically to using wavelet transforms and sorting of wavelet coefficient sets to separate impulsive components from non-impulsive components of a time-domain signal.

This application is related to commonly owned, co-pending U.S. application Serial no. (98-0929), entitled "Method and Apparatus for Identifying Sound in a Composite Sound Signal", which was filed concurrently herewith.

Time-domain signals or waveforms may often include impulsive and non-impulsive components even though only one of these components may be of interest. For example, in either wireless or wired transmission of electrical or electromagnetic signals, interfering signals and background noise contaminate the signal as it travels through the wireless or wired transmission channel. The transmitted signal contains information, and therefore has primarily an impulsive character. The interference and background noise tends to be random and broadband, and therefore has primarily a non-impulsive character. After transmission, it would be desirable to separate the components so that the additive noise can be removed.

In other applications, sound waves may be converted to electrical signals for transmission or for the purpose of analyzing the sound to determine conditions that created the sound. If the sound is a voice intended for transmission, the picked-up sound may include an impulsive voice component and a non-impulsive background noise component. If the picked-up sound is created by operation of a machine or other environmental noise, the nature of the impulsive and/or non-impulsive sound components can be analyzed to identify specific noise sources or to diagnose or troubleshoot fault conditions of the machine, for example.

Prior art attempts to reduce unwanted noise and interference most often treat a signal as though the impulsive and non-impulsive components occupy different frequency bands. Thus, lowpass, highpass, and bandpass filtering have been used to try to remove an undesired component. However, significant portions of the components often share the same frequencies. Furthermore, these frequency bands of interest are not known or easily determined. Therefore, frequency filtering is unable to separate the components sufficiently for many purposes. Fourier analysis and various Fourier-based frequency-domain techniques have also been used in attempts to reduce undesired noise components, but these techniques also cannot separate components which share the same frequencies.

More recently, wavelet analysis has been used to de-noise signals. Wavelet transforms are similar in some ways to Fourier transforms, but differ in that the signal decomposition is done using a wavelet basis function over the plurality of time-versus-frequency spans, each span having a different scale. In a discrete wavelet transform, the decomposed input signal is represented by a plurality of wavelet coefficient sets, each set corresponding to a respective time-versus-frequency span. De-noising signals using wavelet analysis has been done in the prior art by adjusting the wavelet coefficient sets by thresholding and shrinking the wavelet coefficients prior to recovering a time-domain signal via an inverse wavelet transform. However, this technique has not resulted in the desired signals being separated to the degree necessary for many applications.

According to the present invention there is provided a method of separating impulsive and non-impulsive signal components in a time-domain signal, comprising the steps of: decomposing said time-domain signal using a wavelet transform to produce a plurality of sets of wavelet coefficients, each set of wavelet coefficients corresponding to a respective time/frequency span; determining a

respective statistical parameter for each set of wavelet coefficients; and re-synthesising a new time-domain signal using an inverse wavelet transform applied to selected ones of said sets of wavelet coefficients, said selected ones being selected in response to said respective statistical parameters.

Further, according to the presence invention there is provided an apparatus for impulsive and non-impulsive signal separation of an input signal, comprising: a wavelet transformer decomposing said input signal into a plurality of wavelet coefficient sets; a statistical parameter calculator calculating a statistical parameter for each wavelet coefficient set; a classifier identifying an impulsive group of wavelet coefficient sets and a non-impulsive group of wavelet coefficient sets in response to said statistical parameters; and an inverse wavelet transformer for synthesising an output signal from one of said groups of wavelet coefficient sets.

The invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a functional block diagram showing a de-noising process of the prior art;

Figure 2 is a functional block diagram showing an improved signal separation process of the present invention;

Figure 3 is a block diagram showing an implementation of the present invention in greater detail;

Figure 4 is a flowchart showing a preferred method of the present invention; and

Figure 5 is a schematic block diagram showing customized hardware for implementing the present invention.

Wavelet analysis has been used in the past to remove noise from data using a technique called wavelet shrinkage and thresholding. A wavelet transform decomposes a signal

into wavelet coefficients, some of which correspond to fine details of the input signal and others of which correspond to gross approximations of the input signal. Wavelet shrinkage and thresholding resets all coefficients to zero which have a value less than a threshold. This reduces the fine details which is where certain noise components may be represented. Thereafter, the modified coefficients are applied to an inverse transform to reproduce the input signal with some fine details missing, and therefore with a reduced noise level. As shown in Figure 1, a time-domain signal is applied to a discrete wavelet transform (DWT) 10. As a result of the decomposition, a plurality of wavelet coefficient sets 11, individually designated as CS1 through CS8, are produced. Each coefficient set corresponds to a respective time-versus-frequency span and has a plurality of datapoint samples. The number and locations of the time-versus-frequency spans are selected to maximize performance in any particular application. Typically, the range between an upper and a lower frequency is divided geometrically (e.g., logarithmically) into the desired number of time-versus-frequency spans. The plurality of coefficient sets 11 are each adjusted according to the thresholding criteria of the wavelet shrinkage and thresholding technique in a plurality of adjustment blocks 12. The adjusted coefficient sets are provided to an inverse discrete wavelet transform (IDWT) 13 which reproduces a de-noised time-domain signal.

While the technique of Figure 1 can be effective in reducing gaussian-type noise in a noisy data signal, the degree of signal separation obtained in certain applications (such as clearly separating impulsive and non-impulsive, non-gaussian components) is not fully achieved. Such signal separation is greatly improved using the present invention as shown generally in Figure 2. A time-domain input signal 15 is input to a wavelet transform 16. A plurality of resulting wavelet coefficient sets are input to a kurtosis calculation 17. A kurtosis value β is determined for each of the wavelet coefficient sets according to the ratio of

the fourth-order central moment to the squared second-order central moment of the individual coefficient values within each wavelet coefficient set. Each coefficient set has about the same number of datapoints as input signal 15. Each wavelet coefficient set corresponds to a different level or scale of the wavelet transform. Rather than modify values within each respective wavelet coefficient set as in the prior art, the present invention sorts the wavelet coefficient sets according to the respective kurtosis values or with respect to some other statistical parameter. Based upon this sorting of coefficient sets, the respective impulsive and non-impulsive components of the input signal are separated.

Thus, the wavelet coefficient sets are sorted into coefficient sets 18 having kurtosis values β greater than a predetermined kurtosis threshold and coefficient sets 19 having kurtosis values β less than the predetermined kurtosis threshold. Coefficient sets 18 are passed through an inverse wavelet transform 20 to reproduce the impulsive component 21. Coefficient sets 19 are passed through an inverse wavelet transform 22 to produce the non-impulsive component 23. Either or both of these signal components are coupled to an output device 24 which may include an audio transducer or a video display for reproducing audio and video signals, for example.

The kurtosis value is a preferred statistical parameter for separating the impulsive and non-impulsive components. However, other statistical parameters can be used such as mean, standard deviation, skewness, and variance. Furthermore, the threshold employed for separating the signal components may take on different values depending upon the signal sources. In general, a kurtosis threshold equal to about 5 provides good results.

A specific implementation of the present invention is shown in greater detail in Figure 3. A time-domain signal having impulsive and non-impulsive components which are desired to be separated is input to a discrete wavelet

transform (DWT) 25. A conventional DWT is employed. A selected basis function and the number of spans and locations for each time-versus-frequency span must be specified as is known in the art. A plurality of sets of wavelet coefficients CS1 through CS4 are generated in blocks 26-29. Typically, the number of time-versus-frequency spans is greater than four, but four are shown to simplify the drawing. In many applications, a span number of eight has been found to provide good performance.

CS1 block 26 is coupled to a kurtosis calculation block 30. The kurtosis value from kurtosis calculation block 30 is provided to a classifier/comparator 31. A predetermined threshold is also provided to classifier/comparator 31 and is compared with the kurtosis value. Depending upon the result of the comparison, classifier/comparator 31 controls a multiplex switch 32. The input of multiplex switch 32 receives coefficient set CS1. The switch output may be switched to either an impulsive IDWT 36 or a non-impulsive IDWT 37. Coefficient blocks 27-29 and multiplex switches 33-35 are each connected to respective identical kurtosis calculation blocks and classifier/comparator blocks (not shown). Thus, coefficient sets having a kurtosis value greater than the threshold are provided through their respective multiplex switches to the impulsive IDWT, thereby producing a time-domain impulsive signal. Coefficient sets having a kurtosis value less than the threshold are switched to non-impulsive IDWT 37 to produce a time-domain non-impulsive signal.

A preferred embodiment of a method according to the present invention is shown in Figure 4. In step 40, a basis function, the number and location of time-versus-frequency spans, and a predetermined threshold are selected for a particular application of impulsive and non-impulsive signal separation. One example of an appropriate basis function may be the Debauchies 40 basis function. A preferred number of time-versus-frequency spans is about eight, with the spans covering frequencies from zero to 22 kHz (using a

common sampling rate of 44 kHz for audio signals). The spans are arranged geometrically and do not cover equal frequency ranges. For example, a first span may cover from 11 kHz to 22 kHz. A second span covers from 5.5 kHz to 11 kHz, and so on. A preferred value for a kurtosis threshold may be equal to about five.

In step 41, the input signal data is decomposed into the wavelet coefficient sets. A statistical parameter is calculated in step 42 for each respective wavelet coefficient set. In a preferred embodiment, the standard mathematical function of calculating a kurtosis value is employed using the individual coefficient values within a wavelet coefficient sets as inputs to the calculation. The output of the calculation is a single kurtosis value for the coefficient set. In step 43, wavelet coefficient sets are selected or sorted based on their respective values of the statistical parameter. The preferred embodiment is comprised of selecting the ones of the sets of wavelet coefficients which all have a kurtosis value either greater than or less than the kurtosis threshold, depending upon whether the impulsive or non-impulsive component is desired for reconstruction. In step 44, that component, or both, are re-synthesized from the selected coefficient sets by applying the selected coefficient sets to an inverse wavelet transform. In other words, all the wavelet coefficients within wavelet coefficient sets not to be included in a particular inverse transform are set to zero.

After re-synthesis, signal artifacts may have been introduced since the inverse wavelet transform is processed with truncated (i.e., set to zero) data. A typical artifact is an erroneously increased output value at either end of the time-domain signal. Thus, in step 45 artifacts are removed by throwing away the endpoint samples in the re-synthesized time-domain signal.

The present invention may preferably be implemented using digital signal processing (DSP) programmable general purpose processors or specially designed application

specific integrated circuits (ASICs), for example. Figure 5 shows a functional block diagram for implementation with either a general purpose DSP or an ASIC. An input signal is provided to an analog-to-digital converter 50. The input signal may be digitized at a sampling frequency f_s of about 44 kHz, for example. The digitized signals are provided to a discrete wavelet transform (DWT) 51. After decomposition, DWT 51 provides a plurality of wavelet coefficient sets to a coefficient-set random access memory (CSRAM) 52. The coefficient sets from CSRAM 52 are provided to a bank of transmission gates 53 comprised of AND-gates. Each coefficient set is coupled to two transmission gates which are inversely controlled as described below. The outputs of each pair of transmission gates are respectively connected to either IDWT 54 or IDWT 55. IDWT 54 provides the impulsive output signal after passing the inverse transform signal through a digital-to-analog converter 56. The output of IDWT 55 is connected to a digital-to-analog converter 57 which provides the non-impulsive signal.

Various control inputs are provided to a control logic block 60. Through these control inputs, a user can specify various parameters for the wavelet-based signal separation including the basis wavelet function, the number and location of time-versus-frequency spans, the threshold value, and other parameters such as the sampling rate to be used. The transform-related parameters are provided to a configuration block 61 which configures DWT 51 and IDWT's 54 and 55.

Control logic 60 also provides the threshold value to a threshold register 62. The threshold value is provided from threshold register 62 to the inverting inputs of a plurality of comparators 63-66. The non-inverting inputs of comparators 63-66 receive kurtosis values β for respective coefficient sets from a plurality of kurtosis calculators 67-70, respectively. The output of each comparator controls a pair of transmission gates which correspond to the coefficient set for which the comparator also receives the

respective kurtosis value. The comparator output is inverted at the input to one transmission gate so that the respective coefficient set is coupled to only one of the IDWTs 54 or 55. Thus, the impulsive and non-impulsive signal components are separated and are available at the outputs of the DSP or ASIC and may be selectively used for any desired application.

Based on the foregoing, the present invention automatically detects and separates impulsive signal components (such as static noises in communication signals or road-induced squeaks and rattles in automobiles) from non-impulsive components (such as background noise) for any types of signals using a predetermined threshold. The invention is adaptive to different types of signals and threshold levels. The invention achieves fast processing speed and may be implemented using general or customized integrated circuits. The invention may be used to identify and separate out impulsive noise signatures reflecting abnormalities of machine operations (e.g., bearing failure, quality control issues, etc.). The invention is also useful in communication, medical imaging and other applications where other impulsive noises or information need to be separated such as in the isolation of static noises, extraneous noises, vibrations or disturbances, and others.

CLAIMS

1. A method of separating impulsive and non-impulsive signal components in a time-domain signal, comprising the steps of:

decomposing said time-domain signal using a wavelet transform to produce a plurality of sets of wavelet coefficients, each set of wavelet coefficients corresponding to a respective time/frequency span;

determining a respective statistical parameter for each set of wavelet coefficients; and

re-synthesising a new time-domain signal using an inverse wavelet transform applied to selected ones of said sets of wavelet coefficients, said selected ones being selected in response to said respective statistical parameters.

2. A method as claimed in claim 1, wherein said selected ones of said sets of wavelet coefficients are determined by comparing each respective statistical parameter with a predetermined threshold.

3. A method as claimed in claim 1 or 2, wherein said statistical parameter is comprised of a kurtosis value.

4. A method as claimed in claim 3, wherein said selected ones of said sets of wavelet coefficients are determined by comparing each respective kurtosis value with a predetermined kurtosis threshold.

5. A method as claimed in claim 4, wherein said predetermined kurtosis threshold is equal to about 5.

6. A method of removing non-impulsive signal components from a time-domain signal, comprising the steps of:

decomposing said time-domain signal using a wavelet transform to produce a plurality of sets of wavelet coefficients, each set of wavelet coefficients corresponding to a respective time/frequency span;

determining a respective statistical parameter for each set of wavelet coefficients;

comparing each respective statistical parameter with a predetermined threshold; and

re-synthesising a new time-domain signal using an inverse wavelet transform applied to selected ones of said sets of wavelet coefficients for which said respective statistical parameters are greater than said predetermined threshold.

7. A method of removing impulsive signal components from a time-domain signal, comprising the steps of:

decomposing said time-domain signal using a wavelet transform to produce a plurality of sets of wavelet coefficients, each set of wavelet coefficients corresponding to a respective time/frequency span;

determining a respective statistical parameter for each set of wavelet coefficients;

comparing each respective statistical parameter with a predetermined threshold; and

re-synthesising a new time-domain signal using an inverse wavelet transform applied to selected ones of said sets of wavelet coefficients for which said respective statistical parameters are less than said predetermined threshold.

8. Apparatus for impulsive and non-impulsive signal separation of an input signal, comprising:

a wavelet transformer (25) decomposing said input signal into a plurality of wavelet coefficient sets;

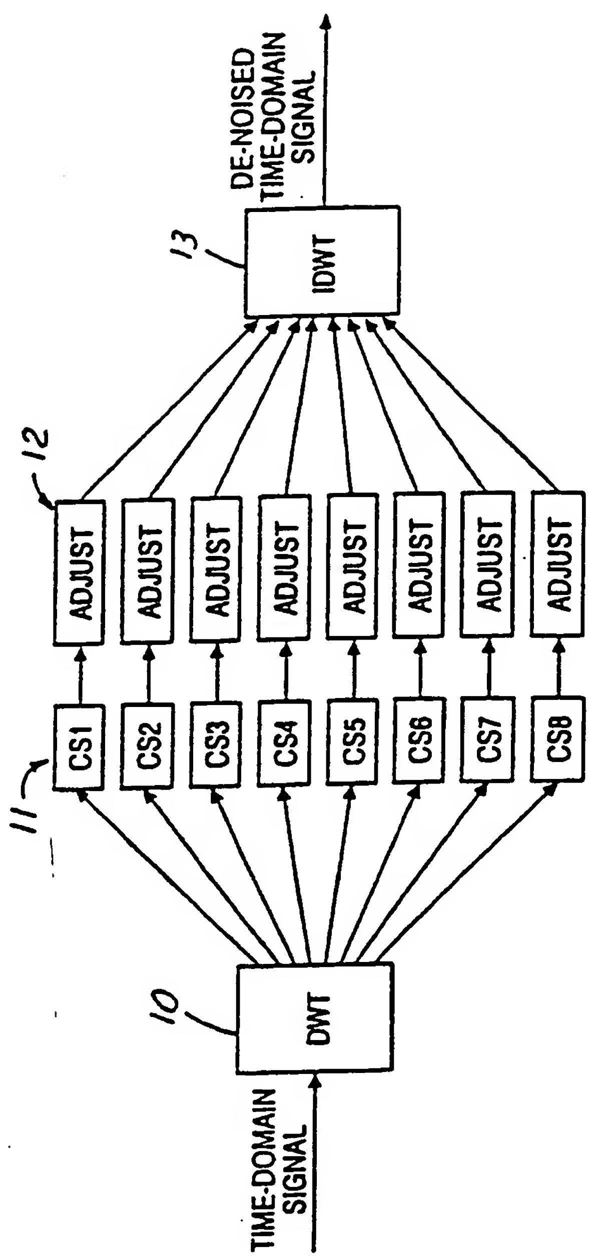
a statistical parameter calculator (30) calculating a statistical parameter for each wavelet coefficient set;

a classifier (31) identifying an impulsive group of wavelet coefficient sets and a non-impulsive group of wavelet coefficient sets in response to said statistical parameters; and

an inverse wavelet transformer (36,37) for synthesising an output signal from one of said groups of wavelet coefficient sets.

9. An apparatus as claimed in claim 8, wherein said classifier identifies said impulsive group of wavelet coefficient sets as those having statistical parameters greater than a predetermined threshold and identifies said non-impulsive group of wavelet coefficient sets as those having statistical parameters less than said predetermined threshold.

10. An apparatus as claimed in claim 9 wherein said statistical parameter is a kurtosis value and said predetermined threshold is a kurtosis threshold.



(PRIOR ART)

FIG. 1

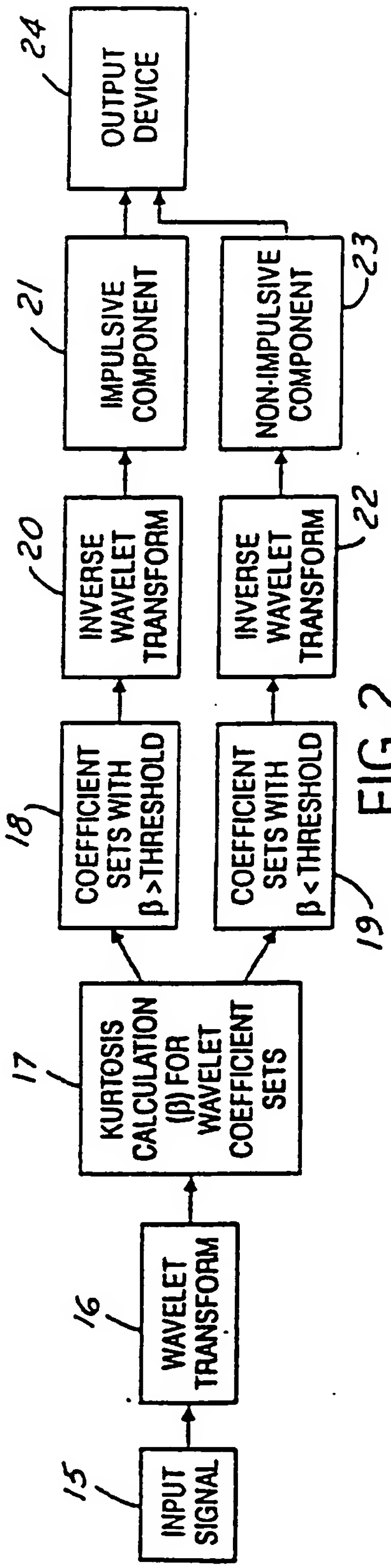


FIG. 2

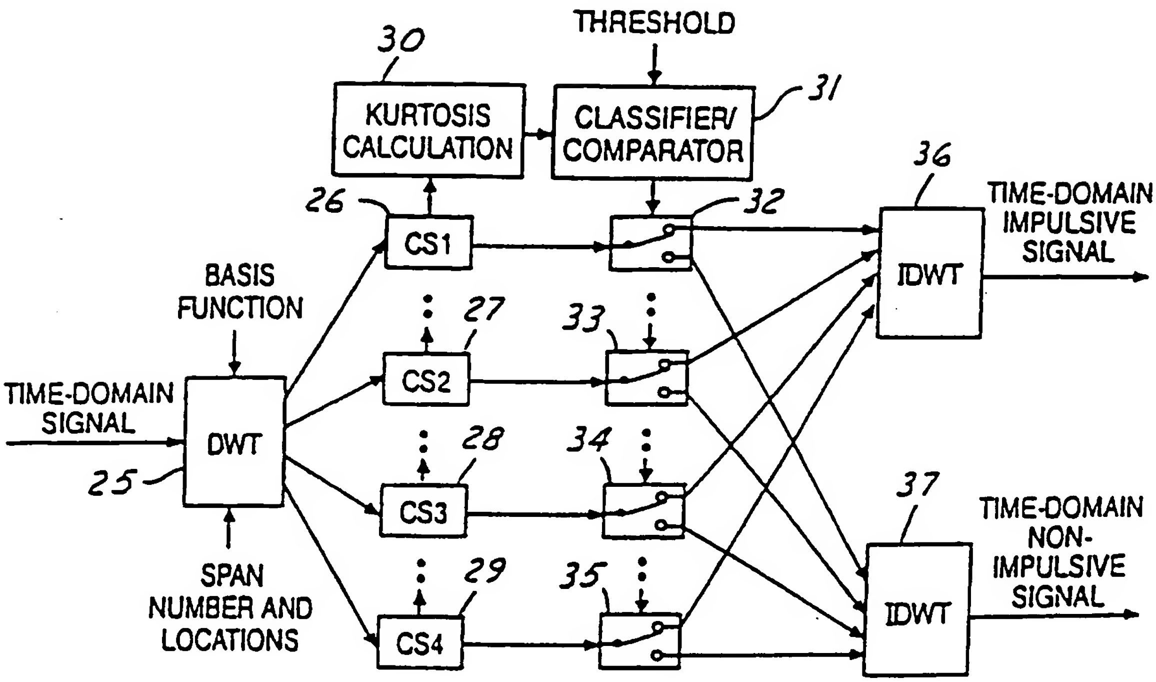

THRESHOLD
30
KURTOSIS CALCULATION
CLASSIFIER/ COMPARATOR
31
36
26
CS1
32
TIME-DOMAIN IMPULSIVE SIGNAL
BASIS FUNCTION
27
33
IDWT
CS2
TIME-DOMAIN SIGNAL
DWT
28
34
25
CS3
37
TIME-DOMAIN NON-IMPULSIVE SIGNAL
SPAN NUMBER AND LOCATIONS
29
35
CS4
IDWT

FIG. 3

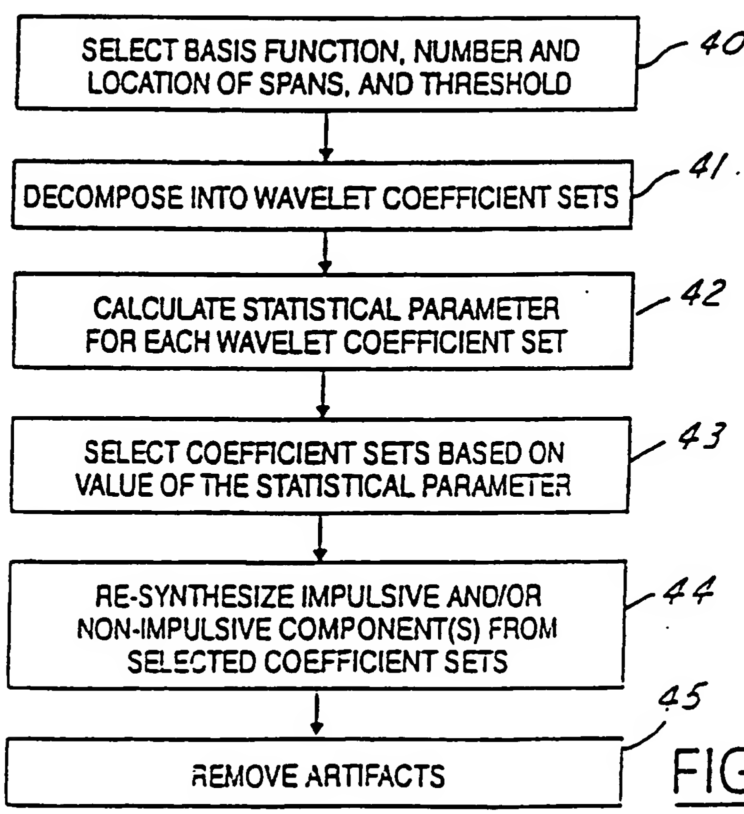
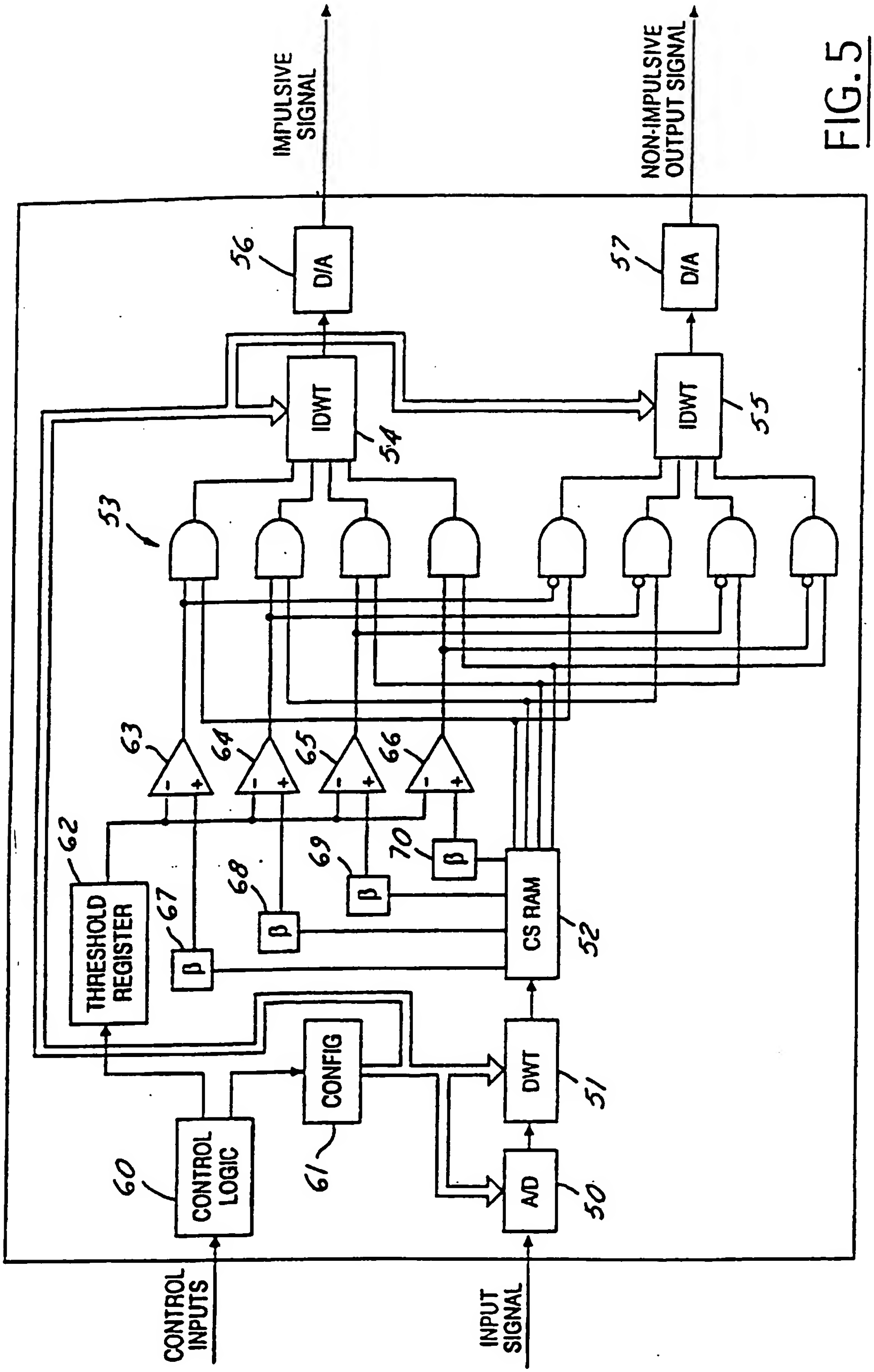

SELECT BASIS FUNCTION, NUMBER AND LOCATION OF SPANS, AND THRESHOLD
40
DECOMPOSE INTO WAVELET COEFFICIENT SETS
41
CALCULATE STATISTICAL PARAMETER FOR EACH WAVELET COEFFICIENT SET
42
SELECT COEFFICIENT SETS BASED ON VALUE OF THE STATISTICAL PARAMETER
43
RE-SYNTHESIZE IMPULSIVE AND/OR NON-IMPULSIVE COMPONENT(S) FROM SELECTED COEFFICIENT SETS
44
45
REMOVE ARTIFACTS

FIG. 4


IMPULSIVE SIGNAL
NON-IMPULSIVE OUTPUT SIGNAL
D/A
D/A
IDWT
IDWT
THRESHOLD REGISTER
β
β
β
β
CS RAM
CONFIG
DWT
CONTROL LOGIC
A/D
CONTROL INPUTS
INPUT SIGNAL
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53
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FIG.5

International Application No
P(.../IB 99/01439

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G10L21/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G10L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DATABASE INSPEC 'Online! INSTITUTE OF ELECTRICAL ENGINEERS, STEVENAGE, GB RAVIER P ET AL: "Denoising using wavelet packets and the kurtosis: application to transient detection" Database accession no. 6232160 XP002122333 abstract & PROCEEDINGS OF THE IEEE-SP INTERNATIONAL SYMPOSIUM ON TIME-FREQUENCY AND TIME-SCALE ANALYSIS (CAT. NO.98TH8380), PROCEEDINGS OF INTERNATIONAL SYMPOSIUM ON TIME-FREQUENCY AND TIME-SCALE ANALYSIS, PITTSBURGH, PA, USA, 6-9 OCT. 1998, pages 625-628, 1998, New York, NY, USA, IEEE, USA ISBN: 0-7803-5073-1 page 625, right-hand column, line 1 - line -/--	1-3,6-10

[X] Further documents are listed in the continuation of box C.

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Date of the actual completion of the international search	Date of mailing of the international search report
11 November 1999	26/11/1999

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International Application No
P. /IB 99/01439

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	22 page 626, left-hand column, line 1 - line 25 ---	
A	WONG R S C ET AL: "DENOISING OF LOOW SNR SIGNALS USING COMPOSITE WAVELET SHRINKAGE" IEEE PACIFIC RIM CONFERENCE ON COMMUNICATIONS, COMPUTERS AND SIGNAL PROCESSING,US,NEW YORK, NY: IEEE, vol. CONF. 6, page 302-305 XP000804652 ISBN: 0-7803-3906-1 abstract page 302, right-hand column, line 13 - line 25 page 303, left-hand column, line 1 - line 21 ---	1,6-8
A	RAVIER P ET AL: "Combining an adapted wavelet analysis with fourth-order statistics for transient detection" SIGNAL PROCESSING. EUROPEAN JOURNAL DEVOTED TO THE METHODS AND APPLICATIONS OF SIGNAL PROCESSING,NL,ELSEVIER SCIENCE PUBLISHERS B.V. AMSTERDAM, vol. 70, no. 2, page 115-128 XP004143557 ISSN: 0165-1684 abstract paragraphs ‘03.1!-‘03.2! -----	1,6-8

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